Adaptive Antennas for Third Generation DS-CDMA Cellular Systems

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Abstract: This paper considers the performance of a DS-CDMA system employing adaptive antenna technology at the base station site for both an Umbrella and a Micro-cell in a hierarchical cell structure. The possible advantages and problems from such a deployment are discussed. By exploiting the capabilities of Ray Tracing to provide the complex channel impulse response, a new adaptive antenna simulation model is presented along with some initial results for the performance of well known adaptive algorithms in a multiple interference scenario. These provide insight into how the adaptive antenna operates when used in conjunction with DS-CDMA and illustrate the potential benefits. Finally, propagation measurements are provided in order to validate some of the claimed capabilities.

1. Introduction

The need for mobile radio systems with increased spectrum efficiency is paramount in the drive towards third generation systems [1]. Currently favoured solutions in today's systems include the deployment of smaller cells as well as fixed sector, or multi-beam antennas, at the base station (BS) site. In terms of modulation schemes and access techniques, application of spread spectrum modulation with Code Division multiple access (CDMA) and especially Direct Sequence (DS) CDMA, look to be amongst the favoured approaches.

Recognising that the ambitious requirements of UMTS & FPLMTS can not be fulfilled with the known cellular architectures (macro, micro, pico cells) led to the conception of the idea of a hierarchical cell structure [2 - 3]. The key issue for this type of cell architecture is to apply multiple cell layers to each service area, with the size of each layered cell tailored to match the required traffic demand and environmental constraints (Fig. 1). In essence, microcells will provide the basic radio coverage but they will be overlaid with Umbrella cells to maintain the ubiquitous and continuous coverage required. Especially for the DS-CDMA system, this mixed cell technique gives answers to situations where a possible performance degradation may occur, e.g. fast moving users requiring handover, or black spots in coverage.

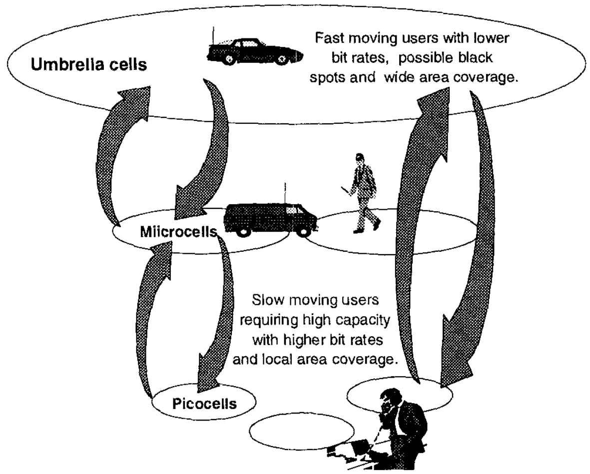


Figure 1: Hierarchical cell structure concept.

Advanced antenna techniques, such as adaptive antennas, is an area which seems to gather momentum recently [4 - 7], as another possible way to increase the efficiency of a given system. Adaptive antennas, based on the spatial filtering at the base station, separate the spectrally and temporally overlapping signals from multiple mobile units. This can be exploited in many ways such as:

- Support a mixed architecture.
- Combat the near-far effect.
- Support higher data rates.
- Combine all the available received energy, (multipath).

In the following section, a brief discussion will be presented on the application of adaptive antennas in an Umbrella cell. The conclusions are taken from an earlier publication [5], but include some additional propagation measurements to support previous claims. The remaining sections focus on the use of adaptive antennas in a microcellular environment operating with DS-CDMA. This work includes the development of a detailed Ray Tracing based simulation model and the presentation of some initial results.

2. An Adaptive Base Station Antenna for the Umbrella Cell of a Mixed Cell Structure

The potential advantages offered by employing an adaptive antenna at an Umbrella BS site with a DS-CDMA system, can be summarised as follows:

- *Mitigation of the near-far effect.*
- *Capacity enhancement.*
- *More efficient handover.*
- *"In-fill" coverage for the dead-spots.*
- *Ability to support high data rates.*

These were discussed in greater detail in an earlier publication [5], although in order to support the last claim, some propagation measurements have been carried out. The measurements were performed with a Fast Fourier Transform (FFT) Dual Channel Sounder at 1.823 GHz [8]. The RMS delay spread was calculated using a 10 dB power window on each measured impulse response profile. The results are shown in figure 2, while figure 3 shows the map of the area where the measurements were performed. For the umbrella cell base station which was at the roof of a building with approximate height 50m, two antennas were used: one omnidirectional end-fed dipole (identical to the mobile antenna) and one directional shrouded yagi with 15dBd gain.

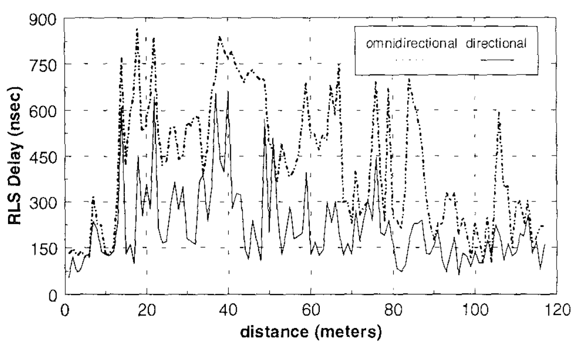


Figure 2: Wideband measurements

From the above figure can be seen that the RMS delay spread is much less for the case of the directional antenna, with a reduction which can be up to 1/5. The reduced delay spread results in less intersymbol interference and, therefore, provides the possibility of supporting higher bit rate services.

3. An Adaptive Base Station Antenna for Small Cells

The angle of arrival (AOA) of the radio signal, along with its multipath components, directly affects the degree of spatial selectivity that can be applied by the antenna system, i.e. whether to form a single narrow beam or adopt an optimum combining approach. In a large cell application, the use of an AOA based approach for a beamformer, would potentially be more desirable since the AOA of the signals has a relatively narrow angular spread [9]. In a microcellular environment, the angular spread of the signal from a single user is much greater, (figures 6b, 6c), due to the lower height of the BS antenna and the close proximity of the scattering objects. Also, the AOA of the signals will change rapidly, with the dominant direction not always towards the desired user, as in the large cells case. Therefore, in the microcellular case, the optimum combining approach seems to be more flexible, providing increased capacity, as it will be shown in the following sections.

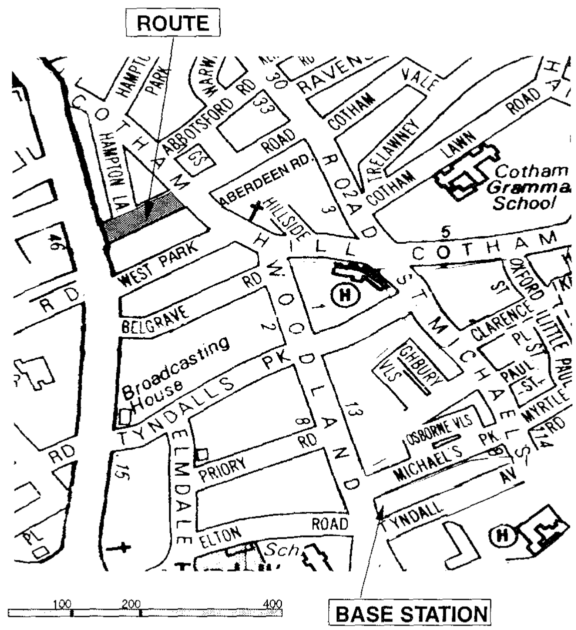


Figure 3: Map of the area under investigation

4. Simulation Model

The simulation model can be separated into two basic blocks:

a) The block which generates the impulse response of the channel under investigation. This is done with the help of a Ray Tracing simulation tool developed by the University of Bristol [10]. The input parameters include the number of reflections and diffractions, the transmitted power, antenna radiation patterns, etc. The resultant output file includes the time delay, the angle of arrival and the power of each received ray.

b) The block which simulates the adaptive antenna array, illustrated in the next figure 4.

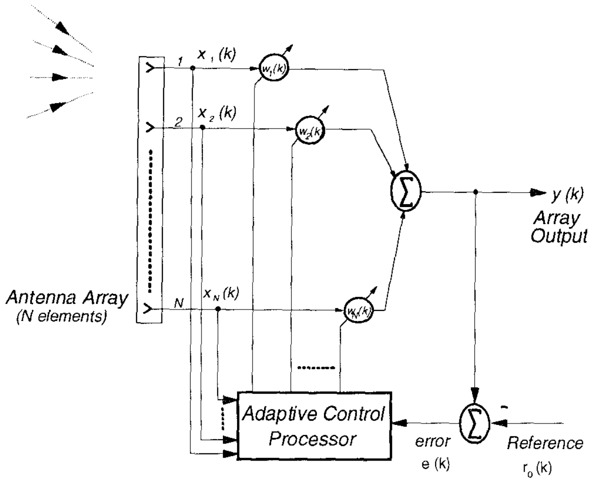


Figure 4: Adaptive Antenna Array

$x_n(k)$ is the sample of the total received signal at the nth element at instant $t = kT$, where T is the sampling interval, as well as being the chip duration of the PN sequence. $x_n(k)$ consists of the desired and interfering DS-CDMA signals and random noise, and it can be expressed as:

$$x_n(k) = \sum_{m=1}^{M} \sum_{r=1}^{R} h_{mr} e^{jkd(n-1)\sin(\vartheta_r)} r_m(k - t_r) + N(k) \quad (1),$$

where h_{mr} and $r_m(k)$ are the elements of the vectors of the impulse response and the DS-CDMA signal from the mth user respectively:

$\mathbf{h}_m = [h_{m1}, h_{m2}, \cdots, h_{mr}, \cdots, h_{mR}]^T$,

$\mathbf{r}_m = [r_m(k), r_m(k - t_1), \cdots, r_m(k - t_r), \cdots, r_m(k - t_R)]^T$.

$\mathbf{r}_m(k) = \mathbf{d}_m(k) \cdot \mathbf{PN}_m(k) \cdot e^{j\varphi_m}$, with $\mathbf{d}_m(k)$ the binary data and φ_m the carrier phase of user m. $N(k)$ represents the random Gaussian thermal noise. M is the total number of users, R is the total number of rays, d is the interelement distance, ϑ_r and t_r are the angle of arrival and the delay of each ray r respectively and $[\ ]^T$ denotes the transpose. Although the total received signal at the nth antenna element is calculated by considering the interelement phase shift for each incoming ray, $(n-1)kd\sin(\vartheta_r)$, depending on the environment under investigation, it can also be calculated directly from the ray tracing tool.

The output from the adaptive array in vector notation is:

$y(k) = \mathbf{w}^T(k)\mathbf{x}(k)$,

where $\mathbf{w}(k)$ and $\mathbf{x}(k)$ are the weight and element vectors respectively. Using (1), this gives:

$$y(k) = \sum_{n=1}^{N} w_n(k) \left\{ \sum_{m=1}^{M} \sum_{r=1}^{R} h_{mr} e^{jkd(n-1)\sin(\vartheta_r)} r_m(k - t_r) + N(k) \right\}$$

where N is the total number of antenna elements. The desired, or reference signal, $r_0(k)$ is simply the PN sequence from one user, (i.e. no data modulation is considered at the moment), and the error signal is defined as the difference between the array output and the desired signal $e(k) = y(k) - r_0(k)$.

This model for the adaptive antenna offers the capability of selecting one from several adaptive processing algorithms, such as the LMS, NLMS, RLS, SQRLS and the DMI, [11 - 13].

5. SIMULATION RESULTS

The aim for the simulations is to investigate the performance of the adaptive algorithms on an environment basis and to provide insight into the mechanism followed by the adaptive antenna, when operating in conjunction with DS-CDMA. Parameters used in the simulations include: averaging over 15 runs, 8 antenna elements with half wavelength spacing, 1023 chips M-sequence with 1.25 MHz chipping rate, *step* for the LMS and NLMS algorithms 0.01 and a value of 1 for the *forgetting factor* for the RLS and the SQRLS algorithms.

From figure 5 can be seen that, as it was expected, the recursive least squares algorithms, converge very fast, (within around 50 samples, while neither of the LMS - NLMS have reached the same level even after ten times that time). The RLS and the SQRLS algorithms have very similar behaviour, with the SQRLS giving the best output and being more robust. The choice of an adaptive algorithm must be made on the basis that the algorithm must be able to rapidly acquire and track the signals in a variety of mobile scenarios. Therefore the obvious choice is either of the RLS - SQRLS algorithms. In the following simulations the RLS algorithm is used.

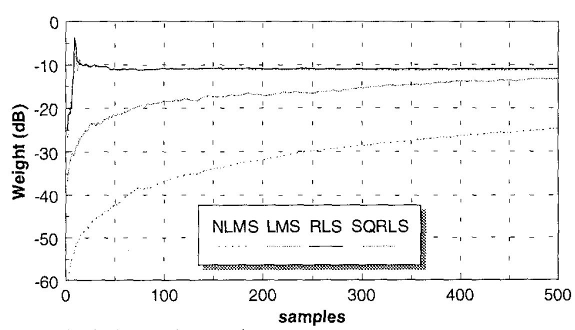
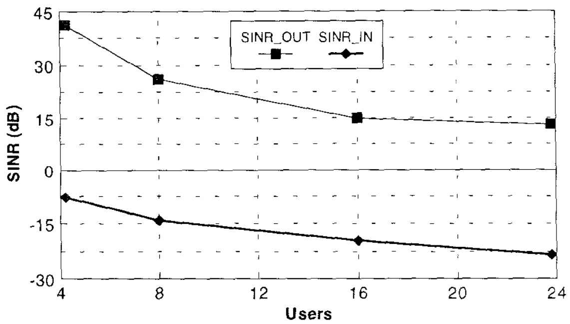
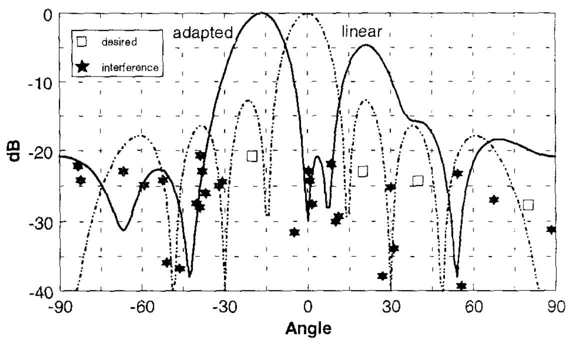


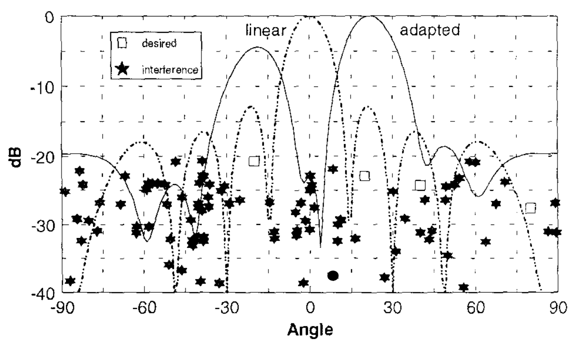
Figure 5: Mean weight convergence for different algorithms, with 16 users.



(a)



(b)



(c)

Figure 6: (a) Output SINR for the RLS algorithm as a function of the number of users, (b) & (c) Produced radiation patterns for 8 and 24 users respectively.

The results depicted in figure 6 show that the array is capable of adapting to the given user scenario even with as many as 24 users. It has to be mentioned here that the SINR values shown in figure 6a are the mean values after convergence. By comparing the results depicted in figures 6b and 6c, the concept of the "smart" antenna is revealed: Although the array should direct its main lobe towards the ray with the maximum incoming power, its first sidelobe towards the next ray with the next maximum power and so on, it doesn't do so for the case of figure 6c. The reason for this behaviour is that the criterion used by the adaptive algorithm is the optimum SINR. This is going to be achieved by steering the main lobe towards the second desired ray rather than steering it towards the first desired ray, because there is much more interference around the first ray which would be accommodated by the main lobe and hence would decrease the output SINR.

If better output SINR than the one depicted in figure 6a, is needed, then an increase in the antenna elements would offer great improvement, as it is depicted in figure 7.

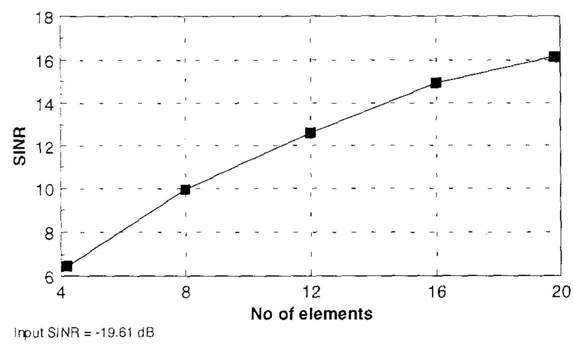


Figure 7: Output SINR for the RLS algorithm and 16 users as a function of the number of antenna elements.

Simulations showed that the influence of the thermal noise (modelled as White Random Gaussian noise), to the adaptive antenna performance is negligible. For example, for a microcellular environment with 16 users and the RLS or the SQRLS algorithm, there is a reduction of less than 0.4dB in the output SINR. This maximum reduction corresponds to the rather worst case situation of an input SNR of 3dB. The above behaviour can be explained on the ground that the influence of thermal noise in a system can be neglected when traffic in the system is close to its capacity limit, because then interference power becomes a dominant factor for determining communication quality and channel capacity. This obviously is even stronger for the case of DS-CDMA.

6. Discussion

The advantage from using an adaptive antenna with a DS-CDMA system is two-fold:

First, the output SINR is greatly improved, which corresponds to an improvement on the capacity of DS-CDMA, which can be substantial.

Second, the produced radiation pattern has a directionality which varies according to the environment under investigation. For an umbrella cell scenario, due to the small number of signals and their very narrow angular spread, the produced radiation pattern can be very directional, which can be exploited in a number of ways as it was described in [5]. Even for the microcells, where the number of users is great and the angular distribution of the incoming signals very wide, the produced radiation pattern is going to be better than an omnidirectional pattern (even slightly). Obviously, the pattern oriented analysis for the benefits achieved with an adaptive antenna, (discussed in [5]), can not be applied for the case of microcells.

In a system like the DS-CDMA, the optimisation process must be repeated cyclically for each desired user. This can be done either in parallel with the help of a bank of beamformers or with one time shared beamformer. Considering as an example, the case of a channel which is sampled every 1ms, the following can be mentioned:

- For the case of an umbrella cell with 10 users, the time available to the Beamformer to optimise its response for each user in a serial mode, corresponds to 125 samples for a 1.25MHz PN sequence. This means that if fast algorithms are used, the use of one Beamformer in a serial mode, can be possible for this kind of cell structures.
- For the case of a microcell with 24 users, the samples available for convergence when one Beamformer is used, are limited to 52. This obviously indicates the need for a bank of Beamformers and parallel beamforming.

7. Conclusions

Work presented in this paper discussed the application of adaptive antennas in a third generation DS-CDMA mixed cell architecture system, at both the umbrella and the microcell base stations. It was shown that an adaptive antenna can be used in order to enhance the performance of a DS-CDMA system. In the microcellular environment, simulation results were presented which employed a Ray Tracing tool to provide the radio channel characteristics.

Work currently under way is investigating the performance of an adaptive antenna in different cellular environments with moving users. Also, different forms of adaptive antennas are considered as a function of the environment they are operating, in an attempt to provide a unified approach for all the different environments.

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